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Dynamic Punch Shear Behavior of Unidirectional and Plain Weave S-2 Glass/SC15 Composites

by Libo Ren, Bazle A. Gama, John W. Gillespie Jr., and Chian-Fong Yen

ARL-CR-535 **March 2004**

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14. ABSTRACT

Dynamic punch shear behavior of unidirectional and plain weave S-2 Glass/SC15 epoxy composites is presented. An incident bar and a transmission tube assembly in compression split-Hopkinson Bar setup is used for the dynamic punch shear study. Dispersion correction methodology is used with "3-wave" analysis to convert the experimental bar data into dynamic load-displacement curves. A methodology for determining the average transverse shear strength of the composite laminates is described. The average transverse shear strength of unidirectional and plain weave composites as a function of displacement is presented.

15. SUBJECT TERMS

wave dispersion, split-Hopkinson Pressure Bar experiment, cylindrical tubes

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1. Introduction

Transverse impact and penetration of fiber-reinforced composites are important in personal protection systems, composite armor, marine, automotive, and aerospace structures. Composite materials absorb impact energy through unique macro- and micro-damage mechanisms. Examples of damage include delamination and debonding between layers and woven tows, out-of-plane fiber shear, hydrostatic crush, fiber breakage, pull-out, and frictional sliding at the fiber matrix interphase due to tension and bending deformations as well as matrix plasticity and cracking. Different impact damage modes of composite laminates under partial and complete penetration of S-2 Glass[*]/SC15 Composite laminates are presented in figures 1 and 2. The penetration resistance or ballistic limit of a composite laminate is often expressed by the ballistic limit velocity, V_{50}. The energy absorbed by the composite laminate per unit weight of the projectile, e_A, is given by

$$e_A = \frac{V_{50}^2}{2}.$$
(1)
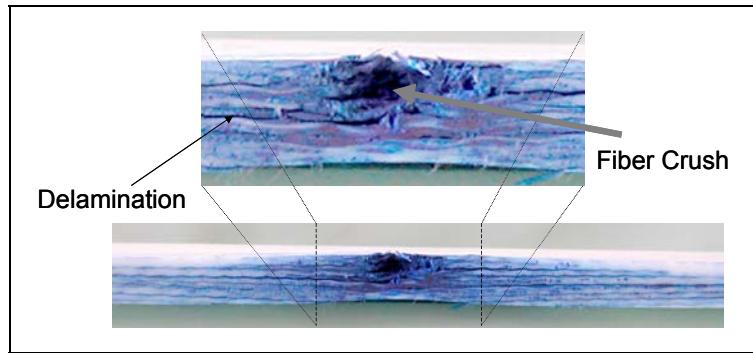
Figure 1. Partial penetration of S-2 Glass/SC15 Composites.

Researchers have investigated the impact damage and penetration of composite laminates and reported the ballistic limit velocities (*1–10*). It has been shown that there are similarities between ballistic impact damage and quasi-static punch shear damage of composite laminates, and efforts have been undertaken to model the ballistic limit of composite laminates using quasi-static punch shear experimental load-deflection curves (*1, 2*). Recent research by the authors (*11*) have identified that energy absorption during punch can be used for relative ranking of composite materials. It has also been identified that the damage modes in quasi-static punch shear depends on the punch to support diameter ratio, $SPR = D_S/D_P$, where D_S and D_P are the diameters of the support and punch, respectively. If, $SPR = D_S/D_P \approx 1$, the damage of the

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[*]S-2 Glass is a registered trademark of Owens Corning.

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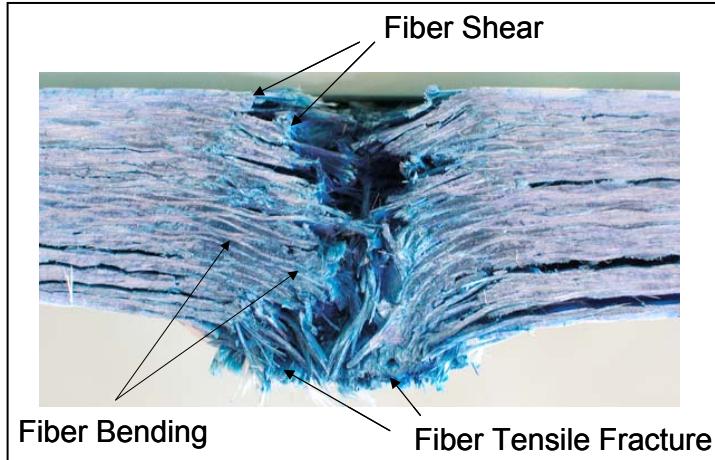
Figure 2. Complete penetration of S-2 Glass/SC15 Composites.

composite laminate is predominantly due to transverse shear. The objective of this study is to characterize the transverse fiber shear strength of S-2 Glass/SC15 epoxy composites under dynamic loading conditions. The transverse fiber shear strength of composite laminates is one of the two important parameters of a recent composite damage model, MAT_COMPOSITE_DMG_MSC, implemented in LS-DYNA for impact and penetration modeling.

2.   Experimental

2.1   Setup

The transverse fiber shear strength of unidirectional and plane weave S-2 Glass/SC15 epoxy composite laminates is experimentally determined under dynamic punch shear loading conditions. Dynamic punch shear tests are usually performed in a compression split-Hopkinson Pressure Bar (SHPB). The analysis of the dynamic punch shear test using a transmission tube and plate specimen is simple and is chosen as the experimental technique for this research effort. The description of this test method is described next.

The dynamic punch shear test is performed using the SHPB apparatus at the University of Delaware–Center for Composite Materials (UD–CCM). A schematic drawing of the test setup with nomenclature is shown in figure 3. The SHPB dynamic punch shear apparatus consists of an incident bar (IB) and a transmission tube (TT). The inner diameter of the TT is slightly greater than the IB diameter, such that the IB bar can punch through the composite specimen (SP) sandwiched between the IB and TT.   A striker bar (SB), powered by the high-pressure gas, impacts the pulse shaper (PS) placed on the impact face of the IB. Depending on the type of pulse shaper used, a compressive stress pulse is produced in the IB. The stress pulse propagates
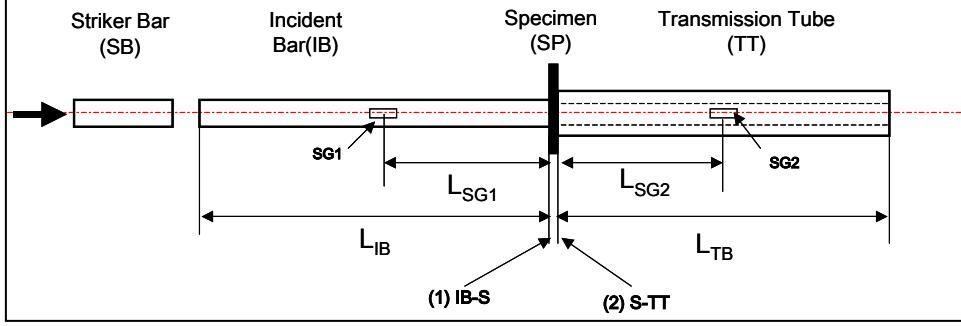
Figure 3. Dynamic punch shear test setup.

along the IB and reaches the incident bar-specimen (IB-S) interface. There, a portion of the energy contained in the pulse will be transmitted to the TT through the specimen while shearing it and the rest will be reflected back into the IB. The propagating stress pulses are measured through strain gages (SGs) mounted on the surface of the IB and TT.

Different dimensions of the present experimental setup are as follows: $L_{IB} = 1653$ mm, $L_{TB} = 762$ mm, $L_{SG1} = 823$ mm, and $L_{SG2} = 327$ mm. The diameter of the IB is $D_{IB} = 14.4$ mm. The outer diameter of the TT is $D_{TT}^{OD} = 25.4$ mm and the inner diameter of the TT is $D_{TT}^{ID} = 15.2$ mm. The diameter of the SB is $D_{SB} = 13.1$ mm. The SB has a length of $L_{SB} = 305$ mm.

Both the IB and the TT are made of Inconel C-276. The density is 8.89 g/cm^3 the Young's modulus is 205 GPa, and the Poisson's ratio is 0.307. The resistance and gage factor of the SGs (SG1 and SG2) (CEA-06-125UT-350, Micro-Measurements, Inc.) are 350 Ohms and 2.115, respectively. A data acquisition system written in LabView is used to collect the experimental data from the SGs. The sampling rate of the data acquisition system is 5 mega samples/s, which corresponds to a time interval between two consecutive data points of 0.2 μs.

2.2   Data Reduction

From the SG on the IB, the incident strain pulse, $\varepsilon_i\,(t)$, and the reflected strain pulse, $\varepsilon_R\,(t)$, are recorded. From the SG on the TT, the transmitted strain pulse, $\varepsilon_{TT}\,(t)$, is recorded. These strain data can then be converted to stress in the bars, $\sigma_i\,(t)$, where the subscript i stands for *I*, *R*, and *TT*. The strain data measured at the SG locations are dispersion corrected and time shifted to the bar-specimen interfaces following a dispersion-correction methodology developed by the authors (*12*, *13*). The dispersion correction methodology described by Lifshitz and Leber (*14*) is used to determine the correct longitudinal wave velocity in the IB. The dispersion correction of the transmission tube is performed by solving the frequency equation developed by Mirsky and Herrmann (*15*, *16*) and the dispersion algorithm developed by the authors (*13*). The dispersion corrected and time shifted data to the bar-specimen interfaces can then be used to compute the displacement and forces at those interfaces following a one-dimensional (1-D) wave propagation analysis. Figure 4 shows the notations used in the present analysis.
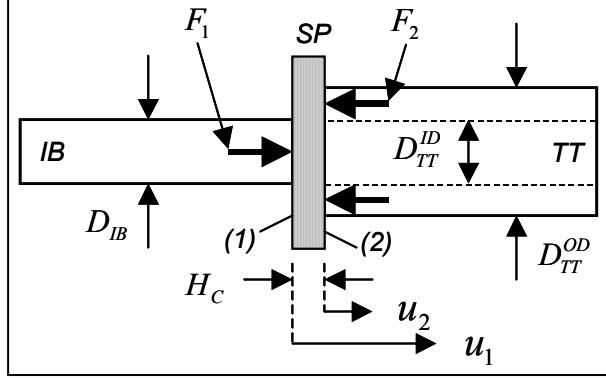
Figure 4. Definition of displacements and forces at the
bar-specimen interfaces.

The displacement and the force at the IB-S (1) interface are defined as u_1 and F_1; and the displacement and the force at the S-TT (2) interface are defined as u_2 and F_1. The displacements at the bar-specimen interfaces can be expressed as follows:

$$u_1(t) = -\int c_0^{IB} \cdot (\varepsilon_I(t) - \varepsilon_R(t)) \, dt, \tag{2}$$

and

$$u_2(t) = -\int c_0^{TT} \cdot \varepsilon_T(t) \, dt, \tag{3}$$

where c_0^{IB} and c_0^{TT} are the corrected/calibrated wave speed of IB and TT following the dispersion-correction methodology. The average displacement of the specimen is defined as

$$u_S(t) = \delta(t) = u_2(t) - u_1(t). \tag{4}$$

The displacement rate is defined as

$$\dot{\delta} = d\delta / dt. \tag{5}$$

The forces acting on the bar-specimen interfaces are defined as follows:

$$F_1 = A_{IB} \cdot E_{IB}^{Corr} \cdot (\varepsilon_I(t) + \varepsilon_R(t)), \tag{6}$$

and

$$F_2 = A_{TT} \cdot E_{TT}^{Corr} \cdot \varepsilon_T(t), \tag{7}$$

where A_{IB} and A_{TT} are the area of the cross section of the IB and TT, respectively. E_{IB}^{Corr} and E_{TT}^{Corr} are the corrected Young's modulus of the two bars after calibration, respectively. The average force acting on the specimen can then be expressed as follows:

$$F_S = (F_1 + F_2)/2. \tag{8}$$

The average dynamic force-displacement curve can then be plotted using equations 4 and 8. The average shear stress can be determined by considering the dimensions of the specimen as in

figure 5, where D_M is defined as the average of punch diameter D_P and tube inner diameter D_S. The thickness of the plate sample is given by H_C. The average shear stress can then be expressed as follows:

$$\tau = F_S / \pi D_M H_C. \qquad (9)$$
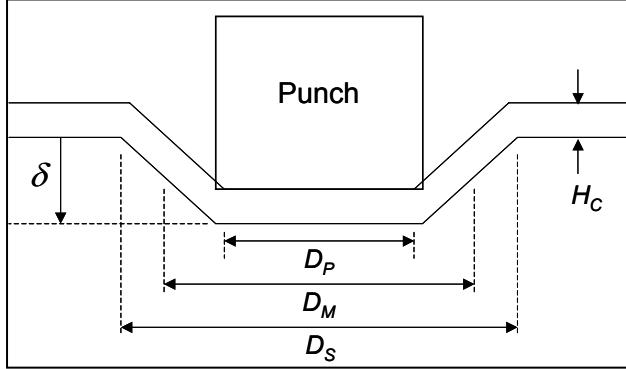
Figure 5. Nomenclatures for the punch shear specimen.

3. Materials

Composite laminates are made from unidirectional S-2 Glass fibers, and 5 × 5 plain weave S-2 Glass fabric preforms (0.81 kg/m^2, 24 oz/yd^2) with API SC15-toughened epoxy resin using vacuum-assisted resin transfer molding (VARTM) process with microflow vacuum control (*17*). The laminates are cured at 43 °C (110 °F) for 8 hr and post-cured at 93 °C (200 °F) for 4 hr under vacuum. Composite laminates obtained following this post-cure cycle have a nominal fiber-volume fraction $0.50 < v_f < 0.55$. After the laminates are made, 50- × 50-mm (2- × 2-in) square specimens are cut from the plate and slot ground on both sides to desired thickness for the dynamic punch shear tests. For unidirectional specimens, the thickness is 2.43 mm. For plain weave specimens, the thickness is 2.2 mm. Using various gas gun pressure values, different displacement rates are obtained.

4. Results and Discussion

Seven unidirectional specimens and five plain weave specimens were tested under dynamic punch shear. Figure 6a shows the stresses as function of time in the IB and TT at the SGs location. Based on the 1-D wave propagation theory, stress is equal to the product of Young's modulus and measured strain. Figure 6b shows the displacements at the IB-S and the specimen-transmission tube (S-TT) interfaces using equations 2 and 3. Figure 6 represents the typical behavior for both the unidirectional and plain weave specimens. From Figure 6a, it can be seen

(a) Bar responses (b) Interface displacements vs. time
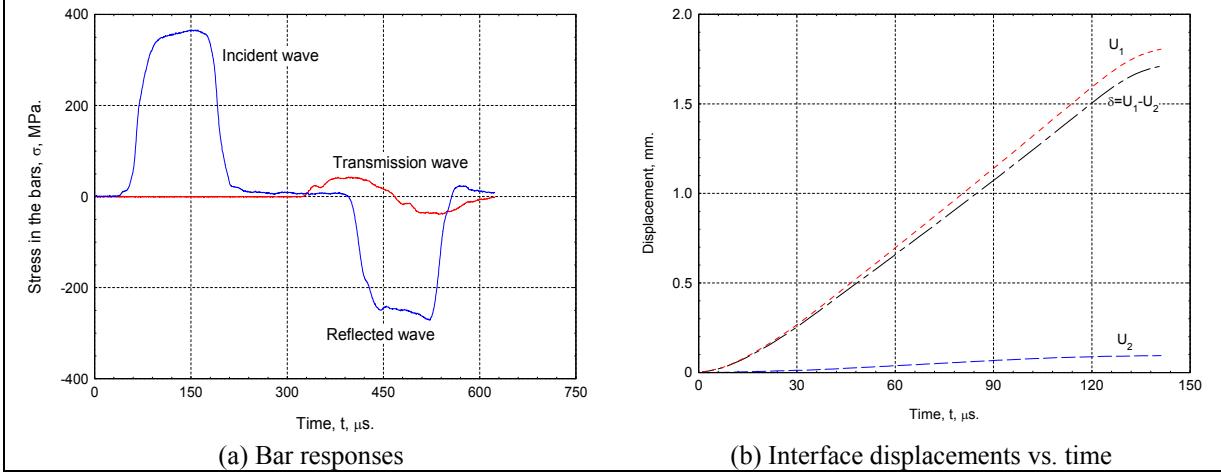
Figure 6. Dynamic punch shear results.

that not much energy is transferred to the TT. From figure 6b, it is seen that displacement u_1 is always much higher than displacement u_2.

Figure 7 shows the interface forces F_1 and F_2 (defined in equations 6 and 7), average force, and equilibrium parameter R, which are defined as $R = 2(F_1 - F_2)/(F_1 + F_2)$. When the specimens are in equilibrium, R approaches to zero. For the general SHPB test, it has been shown that the equilibrium state will be approached after the wave is reflected back and forth inside the specimen multiple times, and R becomes very low. This phenomenon is not seen for the dynamic punch shear test. From figure 7, it is seen that there is always a large difference between the two forces, and R stays >0.2 for most of the period.

(a) Unidirectional specimens (b) Plain weave specimens
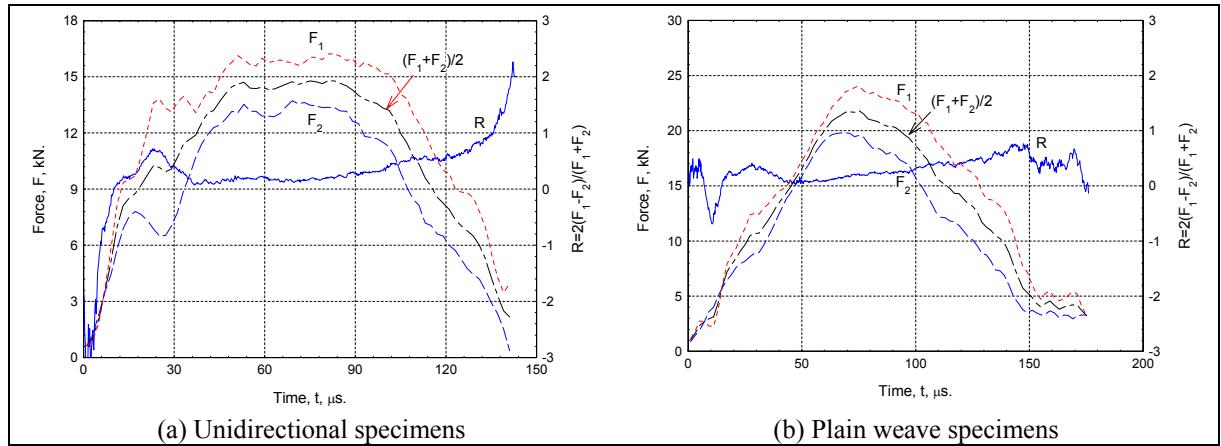
Figure 7. Interface forces and equilibrium parameter.

Comparing figure 7a and 7b, there are obvious differences between unidirectional and plain weave specimens. From figure 7a, it can be seen that F_1 and F_2 deviate from each other at early time; while for plain weave specimen, such deviation occurs much later near the maximum load. There is also a kink in the unidirectional force-vs.-time curve at early time. By examining the

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failed specimens, such difference can be easily explained. Figure 8 shows two unidirectional specimens punched with different speeds (16.3 and 25.0 m/s). On the unidirectional specimens, there are many cracks along the fiber direction, while there are few such long cracks seen on the plain weave specimens. The kink point on the force-vs.-time curve corresponds to the initiation of the first matrix cracks under the shear loading. The matrix cracks continue to develop and propagate in the fiber direction under the dynamic load.

| (a) | (b) | (c) | (d) |
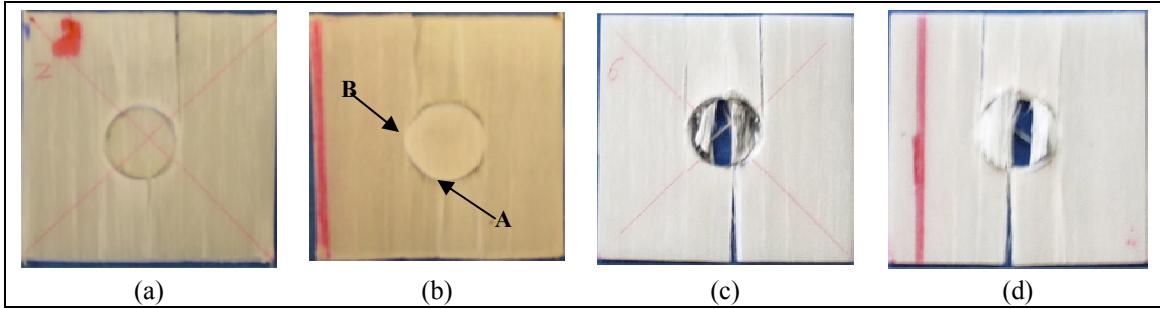
Figure 8. Unidirectional specimens after dynamic punch: (a) and (b) show front and rear sides of one specimen after low-speed punch; (c) and (d) show front and rear sides of one specimen after high-speed punch.

Figure 9 shows two failed plain weave specimens under low (18.1 m/s) and high (25.4 m/s) impact speed. It is obvious that there are no long cracks even after the high-speed impact. The matrix cracks are localized around the punched hole. The failure modes of the unidirectional composites are more complicated than the plain weave composites. While the unidirectional composites showed longitudinal splitting along the fiber direction, for the plain weave composite, matrix cracks can not extend significantly from punch perimeter region because they are arrested by the woven fabric (i.e., orthogonal tows in the fabric). When the load is increased, the area under punch is compressed first, as seen in figure 9a and 9b. When the peak load is applied, fiber tows touching the punch are sheared off, and the tows below enter into a tension state. From figure 8, it can also be seen that when the hole is punched, the region where the fiber is perpendicular to the hole boundary is cut off first (region A), while the region where the fiber is parallel to the hole boundary was cut off to a lesser degree (region B). This can also be seen from the failed specimens under higher speed punch (figure 8c and 8d).

| (a) | (b) | (c) | (d) |
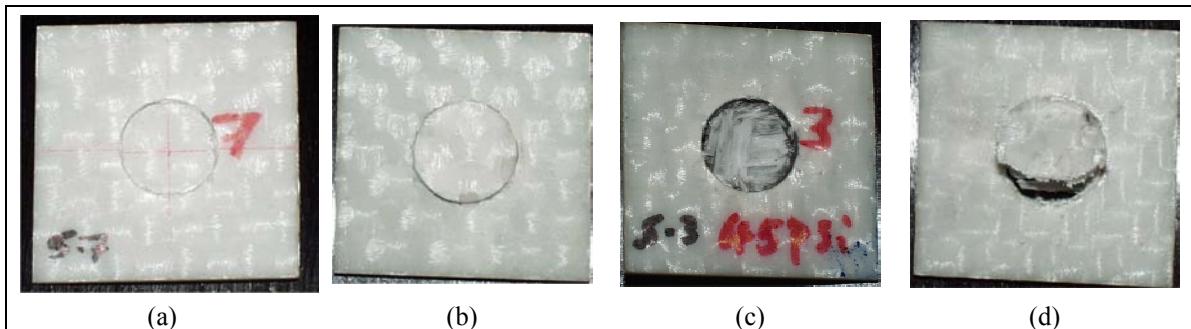
Figure 9. Plain weave specimens after dynamic punch: (a) and (b) show front and rear surfaces of one specimen after low-speed punch; (c) and (d) show front and rear surfaces of one specimen after high-speed punch.

From the viewpoint of energy, some energy is used to propagate the cracks along fiber direction in unidirectional specimens, so there is a large gap between the two interface forces. For plain weave specimens, the energy dissipation due to failure occurs around the punch region and only occurs when the peak load is reached, so the two forces remain close to each other for a longer time.

Figure 10 shows the force-vs.-displacement data for the two materials under various displacement rates. The average shear strength-vs.-strain rate is determined from the peak load as shown in figure 8. The average shear strength is defined as the maximum load divided by the shear surface area. This definition is not very accurate because at the maximum load, the materials did not completely failed, and the surface is not under uniform shear stress, so it is only an approximate representation of the complicated stress state around the hole boundary. On the other hand, this parameter still gives meaningful information. From figure 11, it is seen that plain weave material has a higher shear strength than the unidirectional material, with the difference being ~90 MPa. Secondly, the shear strength increases with the strain rate.

(a) Unidirectional   (b) Plain weave
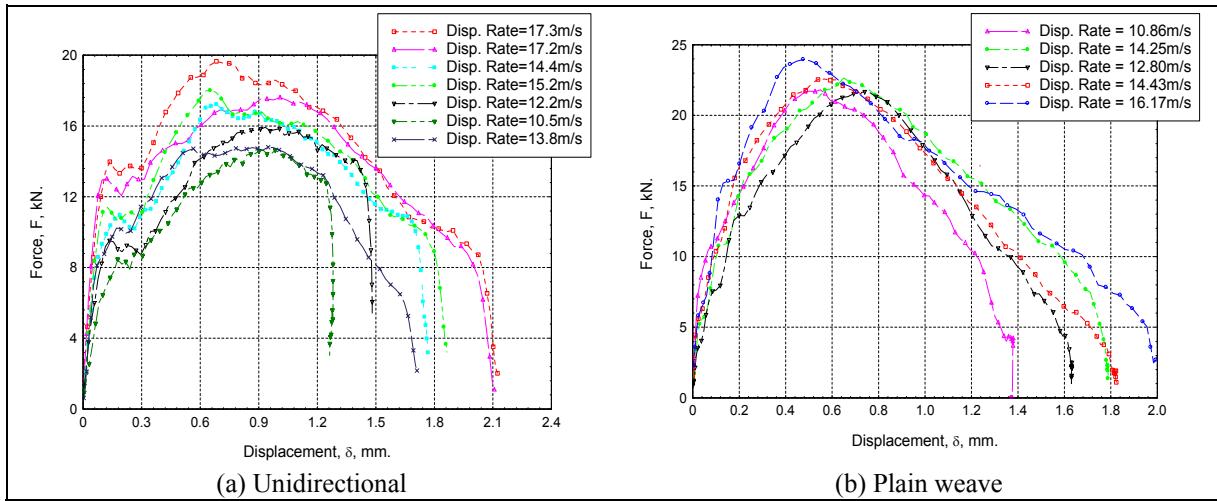
Figure 10. Force-vs.-displacement curves under various displacement rates.
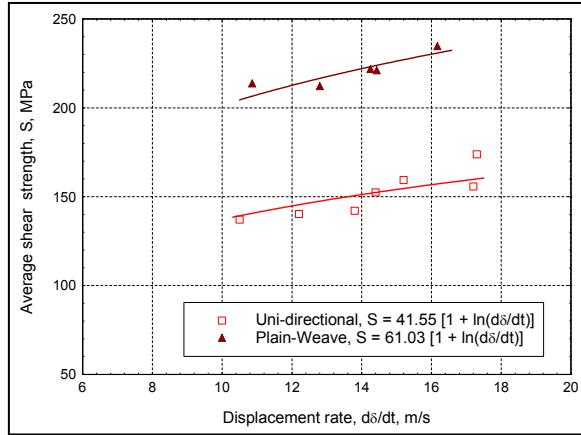
Figure 11. Average transverse shear strength of S-2
Glass/SC15 Composites as a function of
displacement rate.

5.   Conclusions

In this study, the dynamic properties of unidirectional and plain weave S-2 Glass/SC15
Composites were investigated using dynamic punch shear methodology. The experimental data
were formulated in a way, such that the forces and the displacements of the two interfaces can be
expressed as function of time. This formulation is conducive to the understanding of the shear
failure mechanism. The failure modes of the two materials were investigated, and the shear
strength was reported. The unidirectional composites under punch shear loading showed an
additional damage mode, splitting along the fiber direction, as compared to the plain weave
composites. The average transverse shear shear strength of the plain weave composite is found
higher than the unidirectional composite, and this increase is attributed to the woven structure of
the fabric. An increase in strength as a function of displacement rate is observed in both cases of
unidirectional and plain weave composites.

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